In-medium minijet dissipation in Au+Au collisions at $\sqrt{s_{NN}} =$ 130 and 200 GeV studied with charge-independent two-particle number fluctuations and correlations.

Mikhail Kopytine (Kent State University)

for the STAR Collaboration

Abstract

Medium effects on charged-particle production from minijets are studied using three complementary analysis techniques. We find significant angular collinearity and number correlations on p_t even at moderate $p_t < 3$ GeV/c. In this p_t range abundant particle multiplicities enable precision measurements of number correlations of non-identified hadrons for kinematic variables (p_t,η,ϕ). Methods include (1) direct construction of two-particle correlation functions, (2) inversion of the bin-size dependence of non-statistical multiplicity fluctuations and (3) two-dimensional discrete wavelet analysis.

Two-particle correlations on p_t exceed expectations from a model of equilibrated events with fluctuating global temperature. A correlation excess at higher p_t is interpreted as final-state remnants of initial-state semi-hard collisions. Lower-p_t correlations exhibit a saddle structure varying strongly with centrality. Variations in the forms and relative strengths of low and high p_t correlations with increasing centrality suggest transport of semi-hard collision products into the lower p_t region as a manifestation of in-medium dissipation of minijets.

Correlations on p_t can be associated with angular correlations on (η,ϕ), using analysis methods (1), (2) or (3). In particular, wavelet analysis (3) is performed in the (η,ϕ) space in bins of p_t (< 2 GeV/c). Observed angular correlation structures include those attributed to quantum correlations and elliptic flow, as well as a localized structure, increasing in amplitude with p_t, and presumed to originate with minijets. That structure evolves with increasing centrality in a way which also suggests dissipation, including an increased correlation length on η which may be related to the influence of a longitudinally expanding medium on minijet fragmentation.

We study structures on different scales...

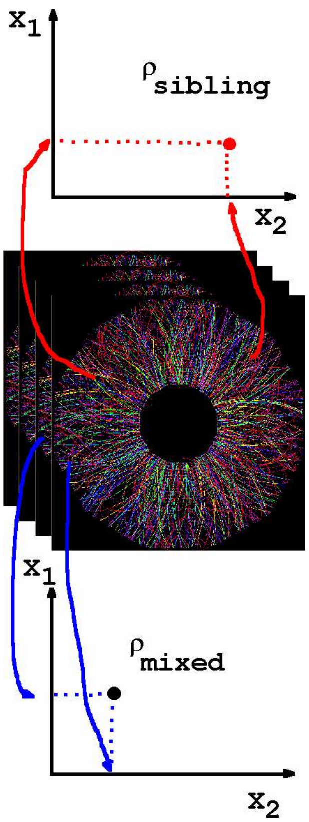
"Fifty Abstract Paintings Which as Seen from Two Yards Change into Three Lenins Masquerading as Chinese and as Seen from Six Yards Appear as the Head of a Royal Bengal Tiger", S.Dali, 1963.

How to use HI to learn about bulk properties of QCD in the thermal limit ?

Study response of the strongly interacting medium to the excitation provided by minijet propagation.

$\Rightarrow$**Concept of the measurement:** study variation of correlations with centrality and p_t. Use the bulk of hadrons and large acceptance for precision studies of correlations as a function of scale.

Compression of correlation information...



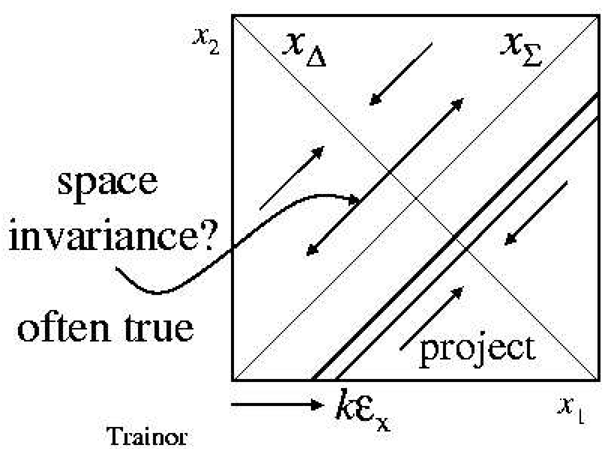
...reduces dimensionality of representation.

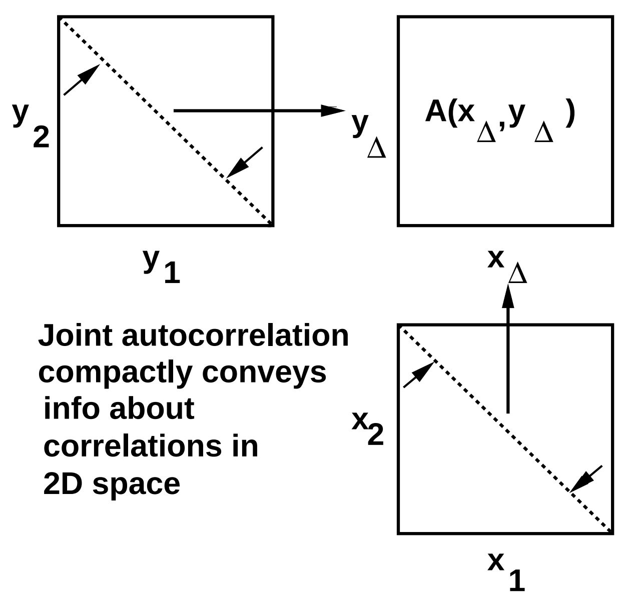
$$\begin{pmatrix} x_1 \\ x_2 \end{pmatrix} \rightarrow \begin{pmatrix} x_\Sigma \equiv x_1 + x_2 \\ x_\Delta \equiv x_1 - x_2 \end{pmatrix}, \qquad (1)$$

always a lossless transformation of data.

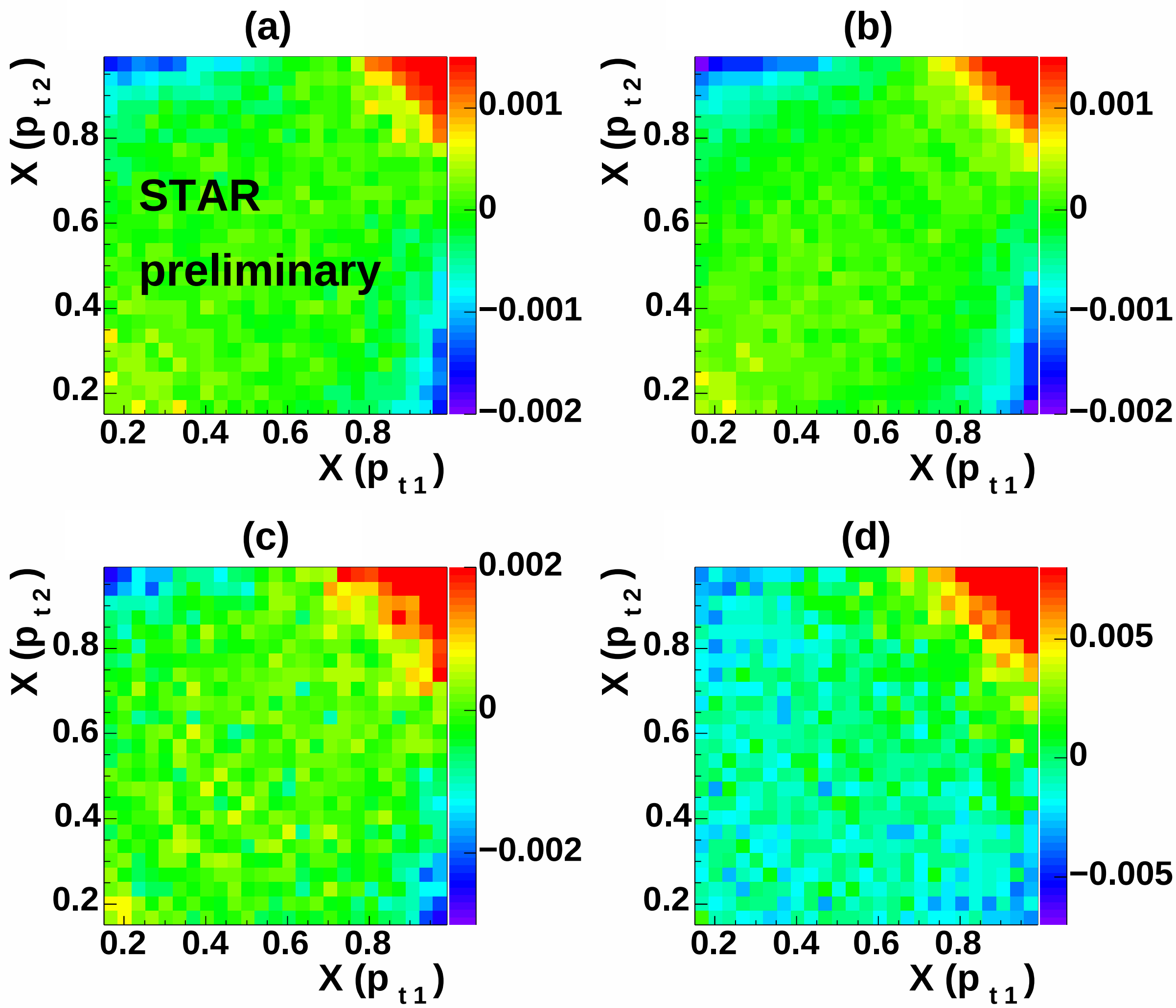
$$\Delta R(x_1, x_2) = \frac{\rho_{sibling}(x_1, x_2)}{\rho_{mixed}(x_1, x_2)} - 1 \qquad (2)$$

Autocorrelation A is a projection of a two-point distribution onto difference variable(s) x_Δ, lossless for x_Σ-invariant (homogenous, stationary) problems.





Two-particle Correlations on p_t



$\rho_{sib}/\rho_{mix}[X(p_{t1}), X(p_{t2})]-1$, pair-density ratios for all unidentified charged primary particles for (a) central, (b) mid-central, (c) mid-peripheral, (d) peripheral AuAu collisions at $\sqrt{s_{NN}} = 130 GeV$.

$$X(p_t) = 1 - \exp[-(m_t - m_\pi)/T] \in [0,1[, T = 0.4 GeV \quad (3)$$

Correlation at higher p_t is "transported" towards lower p_t with increasing centrality.

"Soft fit" − Lévy model: partially equilibrated dissipative system where $\beta = 1/T$ varies according to a Γ-distribution with mean β_0 and variance $\sigma_\beta^2 = \beta_0^2/n$.

$$1/p_t\, dN/\, dp_t \propto [1 + \beta_0(m_t - m_\pi)/n]^{-n} \tag{4}$$

Mixed pairs:

$$\rho_{mix} = \text{Lévy(n)} \times \text{Lévy(n)}(m_{t\Sigma}, m_{t\Delta})$$
$$\propto \Big(1 + \frac{\beta_0 m_{t\Sigma}}{2n}\Big)^{-2n}\Big[1 - \Big(\frac{\beta_0 m_{t\Delta}}{2n + \beta_0 m_{t\Sigma}}\Big)^2\Big]^{-n} \tag{5}$$

Sibling pairs:

$$\rho_{sib} = \text{Lévy} \times \text{Lévy}(m_{t\Sigma}, m_{t\Delta}, n_\Sigma, n_\Delta)$$
$$\propto \Big(1 + \frac{\beta_0 m_{t\Sigma}}{2n_\Sigma}\Big)^{-2n_\Sigma}\Big[1 - \Big(\frac{\beta_0 m_{t\Delta}}{2n_\Delta + \beta_0 m_{t\Sigma}}\Big)^2\Big]^{-n_\Delta} \tag{6}$$

Curvatures at the origin:

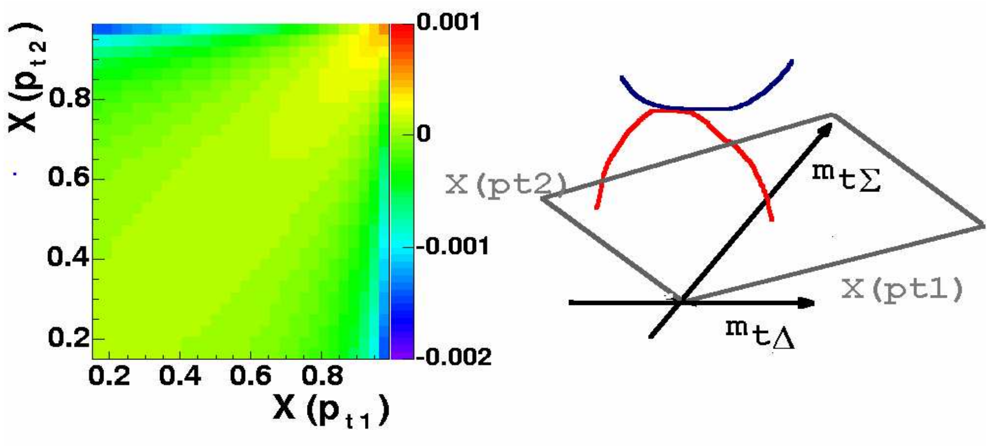
$$\frac{\partial^2}{\partial m_{t\Delta}^2}\frac{\rho_{sib}}{\rho_{mix}}(m_{t\Delta} = 0, m_{t\Sigma} = 0) \propto \beta_0^2\Big(\frac{1}{n_\Delta} - \frac{1}{n}\Big) \tag{7}$$

$$\frac{\partial^2}{\partial m_{t\Sigma}^2}\frac{\rho_{sib}}{\rho_{mix}}(m_{t\Delta} = 0, m_{t\Sigma} = 0) \propto \beta_0^2\Big(\frac{1}{n_\Sigma} - \frac{1}{n}\Big) \tag{8}$$

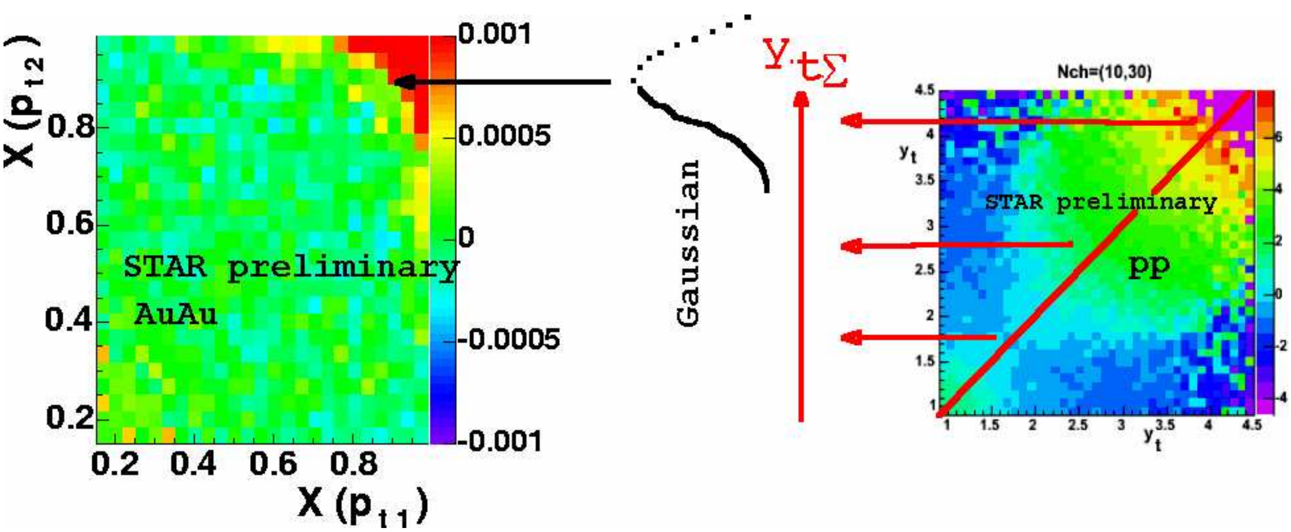
Saddle shape:

$$\Big\{\frac{\partial^2}{\partial m_{t\Delta}^2}\frac{\rho_{sib}}{\rho_{mix}} < 0; \frac{\partial^2}{\partial m_{t\Sigma}^2}\frac{\rho_{sib}}{\rho_{mix}} > 0\Big\} \Rightarrow 1/n_\Sigma - 1/n_\Delta > 0 \tag{9}$$

“Soft” and “Hard” Fitting Models



“Soft” (Lévy) model fit function to $\rho_{sib}/\rho_{mix} - 1$ is saddle shaped.

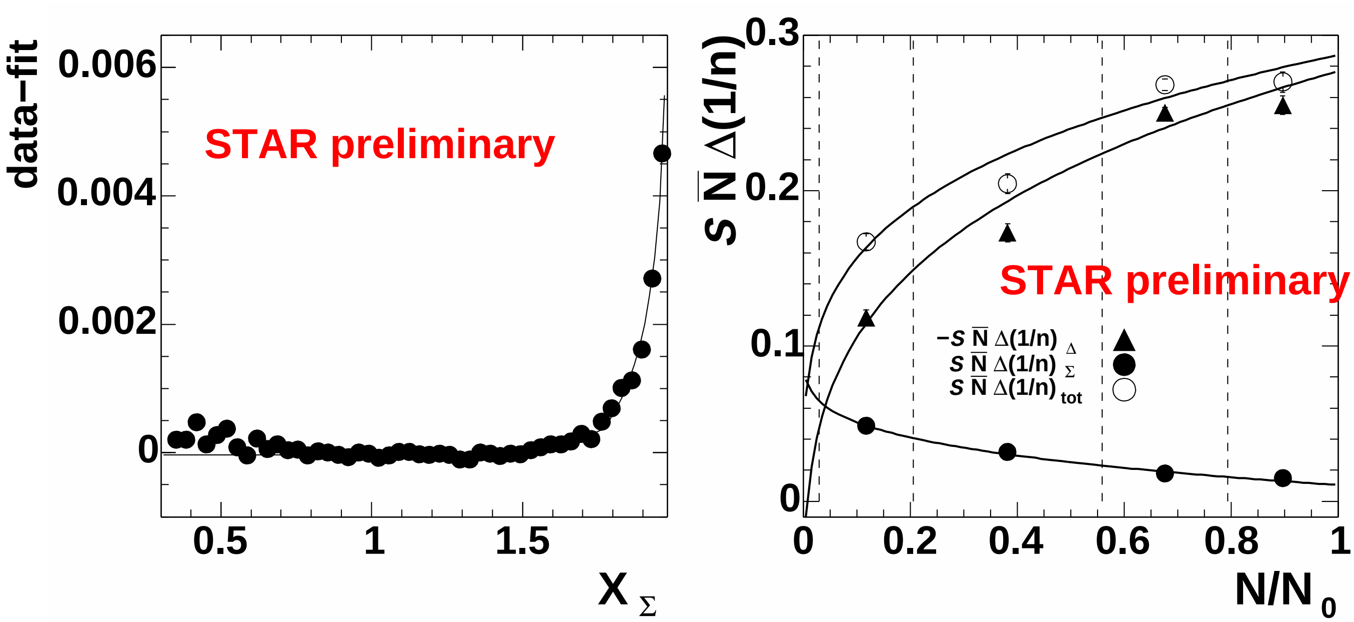


Residuals of the “soft” fit (left panel) are dominated by the large $X(p_t)$ peak $\Rightarrow$ need another, “hard” fit! Correlation in transverse rapidity

$$y_t = \ln\left[\sqrt{1 + (\frac{p_t}{m_\pi})^2} + \frac{p_t}{m_\pi}\right]$$

in pp collisions at $\sqrt{s} = 200$ GeV is gaussian along $y_{t\Sigma}$ $\Rightarrow$ use to fit the “hard component” in $X(p_t)$ in AuAu.

Fitting Results to p_t Correlations



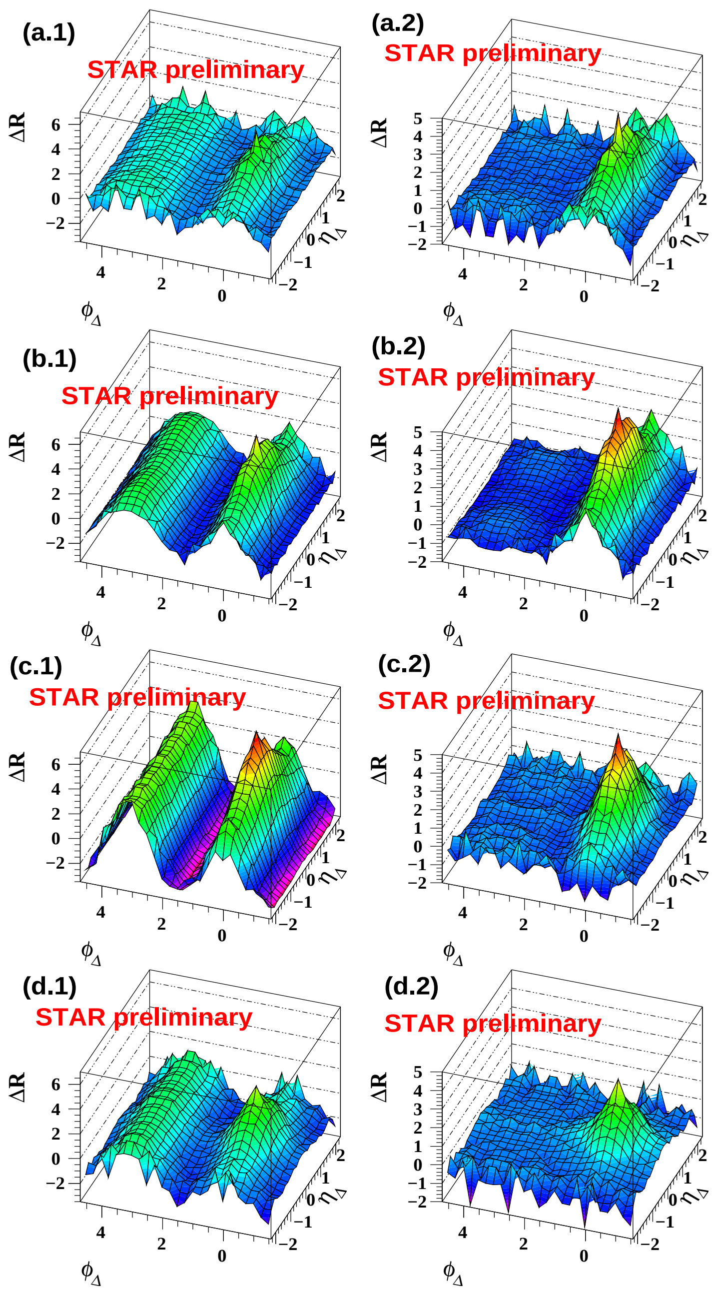
Left, 2D residuals (data−"soft" fit) projected onto X_Σ. "Hard" fit is shown as a line.

Right, centrality trends in the curvature measures. Curves indicate linear trends on mean path length $\nu = (N_{part}/2)^{1/3}$.

$\Delta(1/n)_\Sigma \equiv 1/n_\Sigma - 1/n$ and $\Delta(1/n)_\Delta \equiv 1/n_\Delta - 1/n$ measure curvatures of ΔR along sum and difference variables at (0,0). $\Delta(1/n)_{tot} \equiv 1/n_\Sigma - 1/n_\Delta$ is a measure of the saddle shape.

Thus, the correlation is decomposed into **saddle shape** (dissipation) and **hard component** (high $X(p_t)$ peak). With centrality, the "dissipation" grows with a linear trend on the mean path length.

Determination of two-particle correlations by direct construction of pair ratios



$\rho_{sib}/\rho_{mix} - 1$ as a joint autocorrelation in η_Δ and ϕ_Δ at $\sqrt{s_{NN}} = 130$ GeV. (a) central, (b) midcentral, (c) mid-peripheral, (d) peripheral, (.1) original data, (.2) data with azimuthal flow harmonics v_1 and v_2 subtracted.

The same-side minijet peak broadens in η_Δ from peripheral to central events.

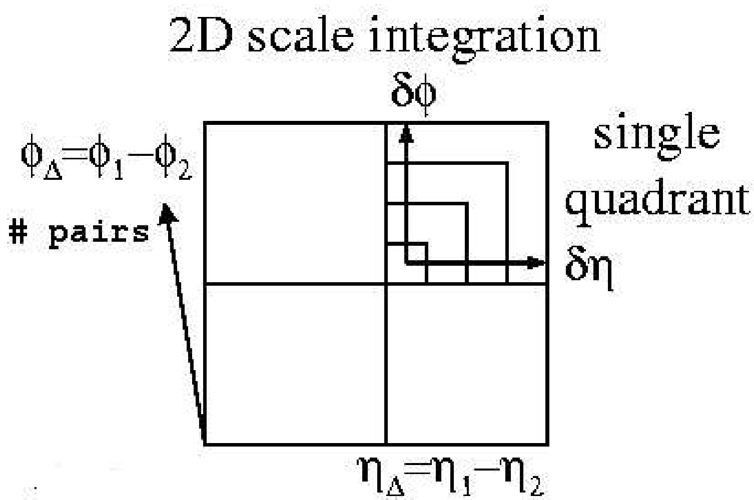
From Scale-dependent Fluctuations to Two-point correlations:

number fluctuation in a $(\delta\eta, \delta\phi)$ bin $(O(N))$

$$\Delta\sigma^2_N = \overline{(N - \overline{N})^2}/\overline{N} - 1 =$$

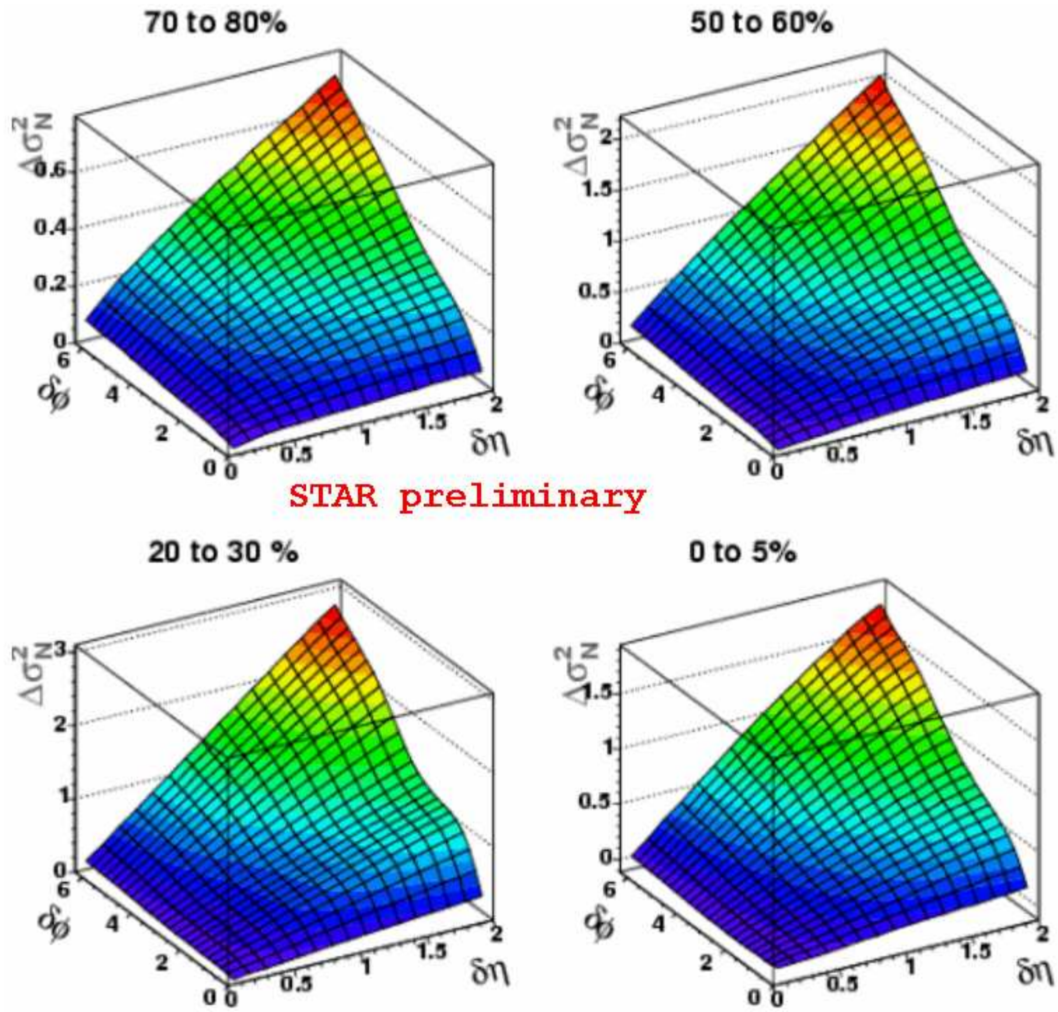
$$\int_0^{\delta\eta} d\eta_\Delta \int_0^{\delta\phi} d\phi_\Delta \mathcal{K}(\eta_\Delta, \phi_\Delta) \overline{N} \frac{\Delta A}{A}(\eta_\Delta, \phi_\Delta) \quad (10)$$

and **net autocorrelation** $\Delta A = A_{obj} - A_{ref}$ $(O(N))$.



Standard methodology for ill-posed problems is used to solve this integral equation. Measure $\Delta\sigma^2_N(\delta\eta, \delta\phi)$, convert to $\overline{N}\frac{\Delta A}{A}$

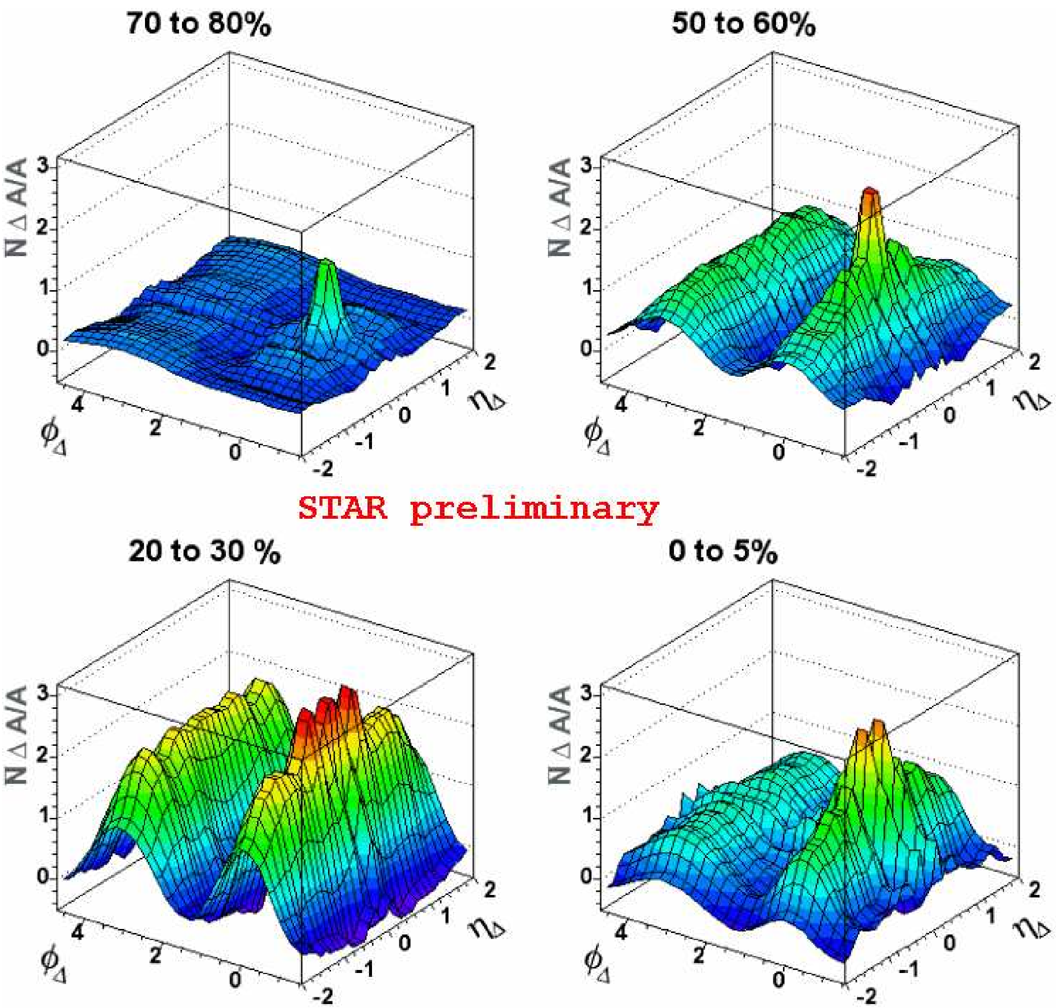
Scale-dependent fluctuations



$\sigma_N^2(\delta\eta, \delta\phi)$ as a function of $\delta\eta$ and $\delta\phi$ in $\sqrt{s_{NN}}$ AuAu data.

These distributions measure scale dependence of total charge fluctuations in bins of scale (bin size) $(\delta\eta, \delta\phi)$. The detailed shapes can be inverted to obtain joint autocorrelations.

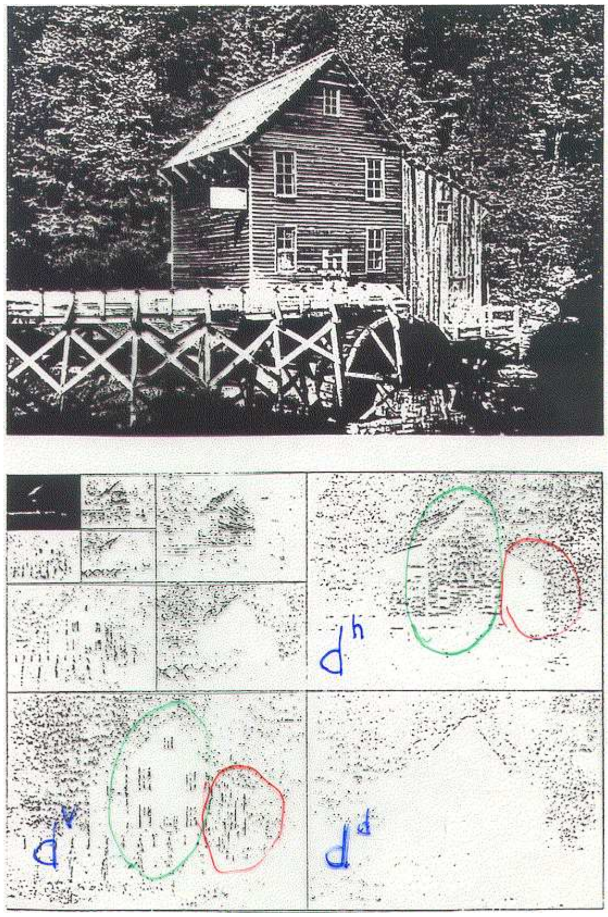
Autocorrelations from fluctuation inversion



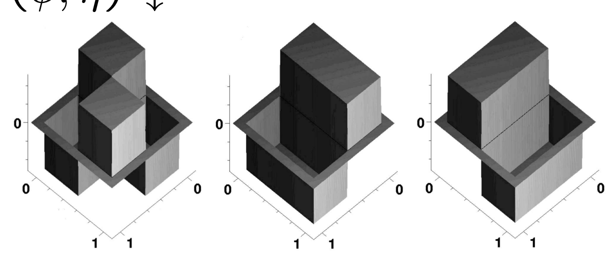
Reconstructed **joint autocorrelations** in particle number; AuAu, 200 GeV, for different centrality %.

Flow and same-side minijet peak are seen; with centrality, peak broadens in η_Δ.

Discrete Wavelet Transformation analysis



$\leftarrow$ Discrete wavelet transformation of a photographic image.
$F^{\lambda}_{m,i,j}(\phi,\eta)$–Haar wavelet **orthonormal basis** in (ϕ,η) $\downarrow$



scale fineness (m), directional modes of sensitivity (λ), track density $\rho(\eta,\phi,p_T)$, locations in 2D (i,j).

Power of local fluctuations, mode λ:

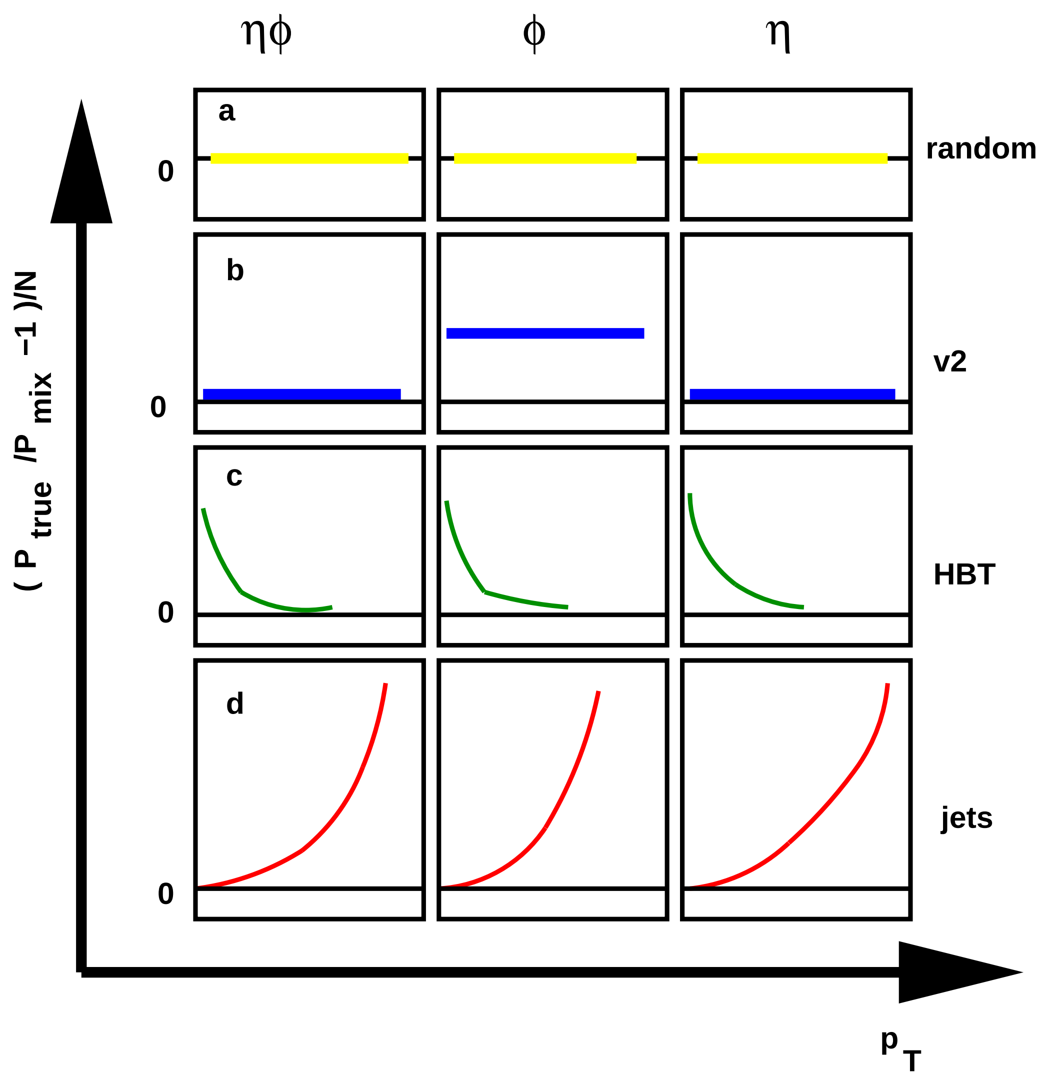
$$P^{\lambda}(m) = \frac{1}{2^{2m}} \sum_{i,j} \langle \rho, F^{\lambda}_{m,i,j} \rangle^2 \qquad (11)$$

$\propto$ **norm** in the DWT subspace

$$(P^{\lambda}(m)_{true} - P^{\lambda}(m)_{mix})/P^{\lambda}(m)_{mix}/N \qquad (12)$$

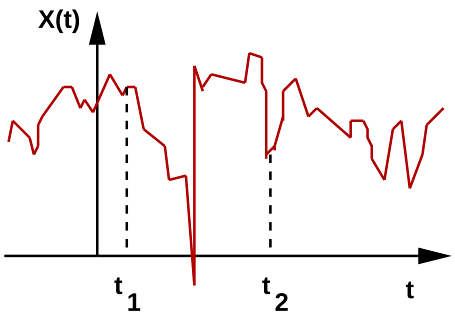
– "dynamic texture" measure

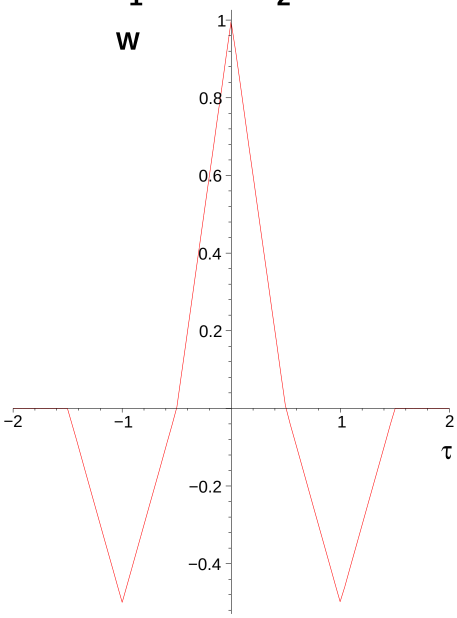
Effects of correlations on the DWT measures:



Dynamic texture response in various idealized situations (showing only one scale): (a) events of random (uncorrelated) particles (b) p_t-independent elliptic flow (c) Correlations at low Q_{inv} (Bose-Einstein correlations and Coulomb effect) (d) HIJING jets

Relating Correlations and Power Spectra:





- Wiener-Khinchin theorem relates autocorrelation $A(\tau)$ with the local fluctuation power spectrum $P(\omega)$ via Fourier transform $\mathcal{F}$.

$$A(\tau) = \int_{-\infty}^{\infty} X(t)X(t+\tau)\, dt$$
$$= \mathcal{F}_{\omega\to\tau}(P(\omega)), \quad (13)$$

$$\begin{array}{ccc} P(\omega) & = & \mathcal{F}_{\tau\to\omega}(A(\tau)) \\ O(N) & \to & O(N^2) \end{array} \quad (14)$$

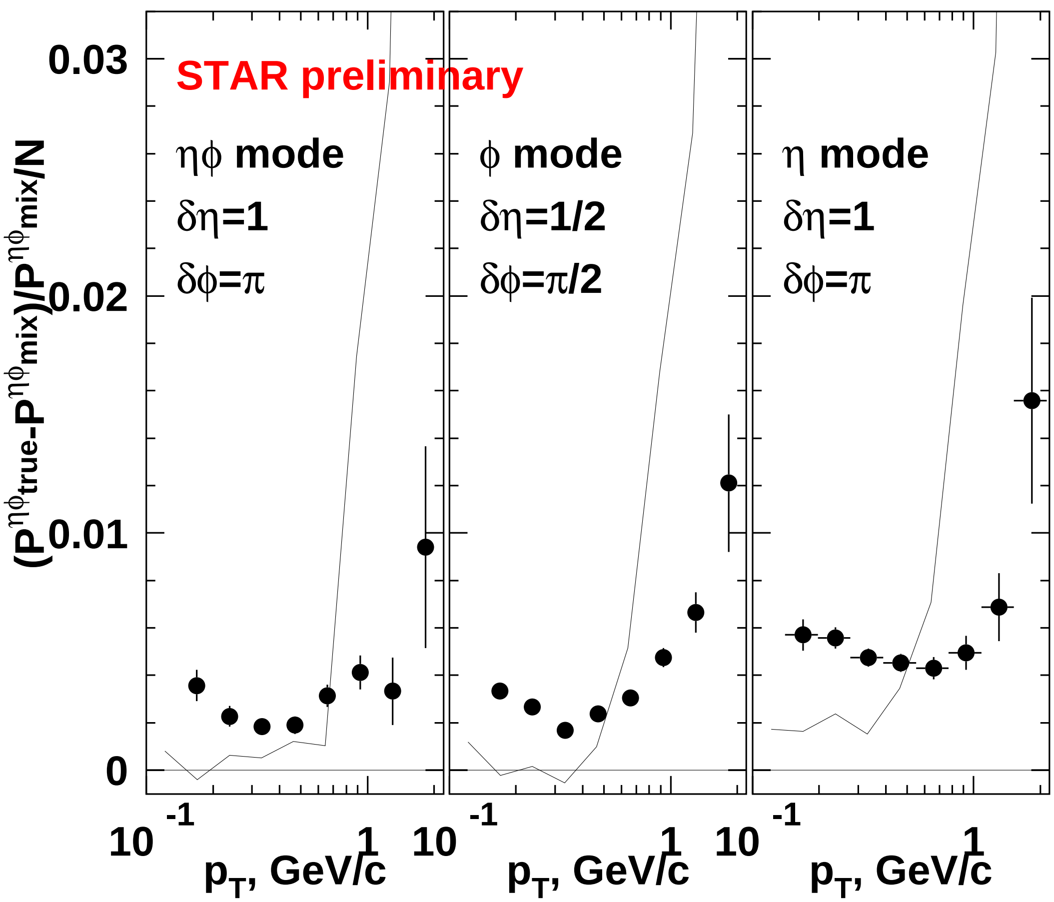
where $\tau = t_2 - t_1$, and $X(t)$ is "homogeneous random field". Prefer $O(N)$ for initial data processing for CPU reasons.

- In the **discrete wavelet** basis, the integral equation 14 looks different:

$$P(m) =$$
$$\int_{-\infty}^{\infty} X(\tau/2)X(-\tau/2)W(\tau, m)\, d\tau, \quad (15)$$

where W is the weight function for the Haar wavelet.

Dynamic Texture in Peripheral Events

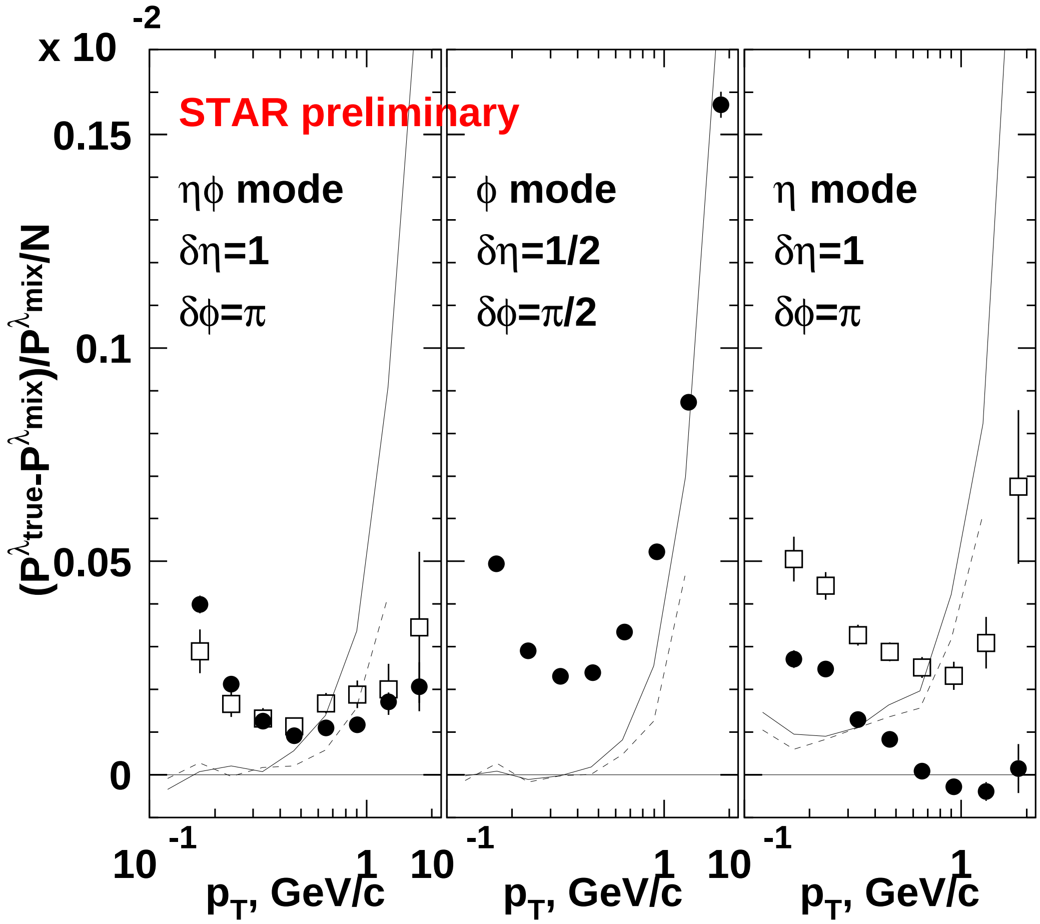


Peripheral ($mult/n_0 < 0.1$) events: •, STAR data for $\sqrt{S_{NN}} = 200$ GeV; solid line, HIJING @ same energy.

Qualitative trends in peripheral data are as expected. What signal to expect in the central data, if correlation does not change ?

$$\left(\frac{P_{true}}{P_{mix}} - 1\right)\frac{1}{N}\Big|_{central} = \left(\frac{P_{true}}{P_{mix}} - 1\right)\Big|_{peripheral}\frac{1}{N_{central}} \quad (16)$$

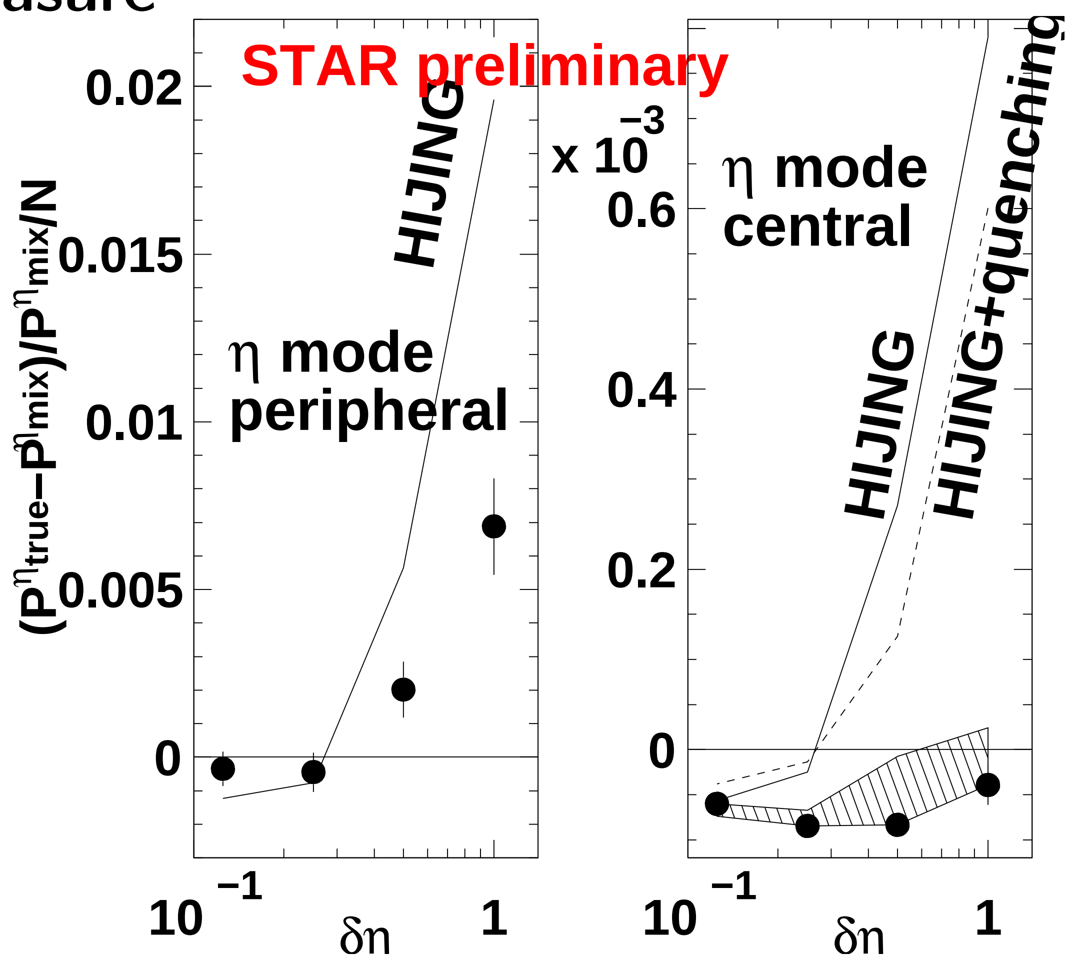
Dynamic Texture in Central Events



•, STAR central ($0.6 < mult/n_0 < 1.1$) events, $\sqrt{S_{NN}} =$ 200 GeV; □, STAR, scaled peripheral; solid line, regular HIJING; dashed line, HIJING+jet quenching.

We are observing a *modification* of the minijet structure predominantly in the longitudinal, η direction. Longitudinal expansion of the hot and dense medium formed early in the collision makes this direction special and is likely to be part of the modification mechanism.

Scale dependence of the dynamic texture measure



...in peripheral and central events for $1.1 < p_T < 1.5$ GeV. •, STAR; solid line, HIJING; dashed line, HIJING with quenching. An estimate of a systematic error due to track merging is shown as a hatched area.

Thermalization, while affecting the correlations (more than HIJING predicts), does not result in a correlation-free system in central events, at least as seen by measuring final state hadrons.

Summary:

- Large multiplicities of hadrons in the STAR acceptance enable precision studies of the event correlation structure.

- Our observations are consistent with an emerging picture: minijets from initial state scattering are modified by longitudinally expanding colored medium.

- These measurments of the effect of the medium on the parton fragmentation and hadronization provide quantitative information about the medium and nonperturbative QCD.